PROPAGATION DYNAMICS OF A MOUNTAIN FIRE: CASE OF *THE YARNELL HILL FIRE 2*

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ABSTRACT

We propose a novel model for the fire evolution, applicable to its spread in mountains, with low-height fuel. Fire propagates along contours of equal elevation on steep terrains. The wind outside the mountain does not conserve on the inside slopes at fuel height. The local wind depends on micro-climatic environment, influenced additionally by the fire itself.

Keywords: wild fires, fire propagation, combustion, environmental, fire, plume, infrared

1. INTRODUCTION

Wild fires start accidentally in the mountains when the lightening strikes. In the dry, hot regions of the Arizona, summer months bring dust and lightening storms without precipitation. The low-precipitation areas are prone to fires, and severe advisories about fire probabilities are a way of life. A very small percentage of lightening-caused fires evolve into a large fire, even smaller percentage into fires that create a pyrocumulonimbus cloud.[1,2,3] We propose a model (see Fig. 1) for the propagation of a fire initiated near a mountaintop that explains significant features of the Yarnell Hill Fire.[4,5,6]

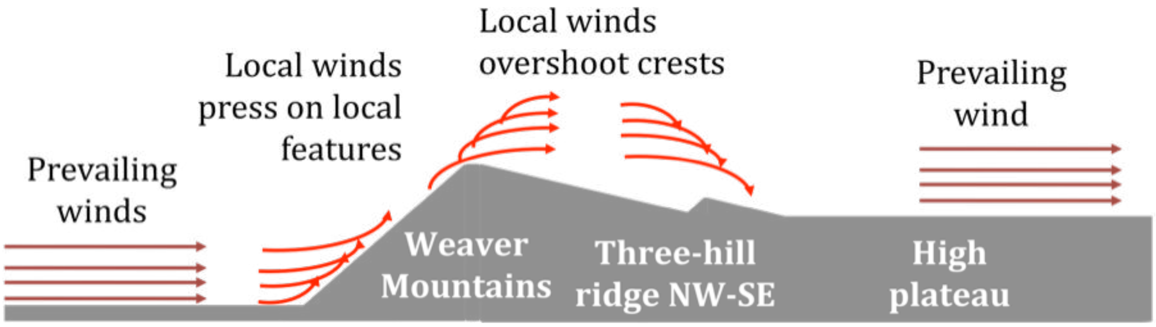

Fig. 1. Prevailing winds blow from S-SW to N-NE direction with daytime speeds of 15 mi/hr. The western slope of the Weaver Mountains often reaches up to 45° incline. On the NE side of the mountains, the high plateau is used for agriculture. When the wind reaches the crest of the Weaver Mountains, the blowing air overshoots the eastern region below the ridge, creating its own microclimate behind the ridge.

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2. MOUNTAIN FIRE PROPAGATION MODEL

We model the fire started in a mountainous region where the elevation may be described by the following equation: $f = f(x,y)$. We define x and y toward E(ast) and N(orth); $z = f$ is local nadir. We analyze the fire propagation, specifically, the fire-front displacement trajectory and its velocity.

In the Figs. 2 through 4, we examine the fire propagation during critical events: including rapid fire expansion 36 hours after fire start; eastward expansion despite reported wind in westward direction; and rapid expansion after fire changed direction by 180 ^{o} in the next four hours.

In all cases, we employ sections of four current (2015) US Geological Survey Maps that form a corner inside the fire area. Green (actually yellow on the processed pages) indicates vegetation, a high chaparral indigenous to the high Sonoran desert. Interestingly, the agricultural vegetation is not indicated this way. The contours are highlighted for 40 ft (12 m) increments in elevation around 6,000, (black), 5,800 (red), 5,600 (dark blue), 5,400 (green), 5,200 (brown), 5,000 (pink), 4,800 (blue) and 4,600 (orange) feet.

2.1 Deceptively slow fire propagation through protected terrains

The lightening strikes on June 28, 2013 at 5:30 pm at about 5,860-ft elevation, indicated with a dark square in the lower left corner of Fig. 1. During the first night, the fire spreads slowly around the area where the lightening has struck, on the SW uphill slope of the Weaver Mountain. There, the fire has been exposed to N-NE winds customary during this season. It easily jumps a single-track road on its E side.

Then the fire propagates N along the equal elevation contours. Interestingly, the speed of fire propagation during the first twenty-five hours is less than its predicted, calculated speed for the fuel and other environmental conditions (including wind speed), generally assumed in determination of fire characteristics and published in Ref. 8. The fire propagation speed is even less than the calculated value for the absence of wind. Considering that such calculations determine the maximum fire-front speed of displacement, we can reasonably conclude that the fire propagates during this time without influence of outside wind. Figure 1 illustrates our understanding of the air movement across the crest in E direction. At the site of fire initiation, the slope is estimated at 45^{o}, as may be appreciated by high contour density. The steep ridge of the Weaver Mountains protects the eastern areas just below it from wind. Precise knowledge (or at least reasonable estimation) of local climate and local wind might offer better understanding of fire-front speed critical to planning the fire-control strategies.

With the wind direction N-NE and terrain slope downhill from the ridge running N-NW to S-SE, the fire is nudged slowly to lower elevations. During the second night the fire front comes to the saddle point at 5,200 ft, in brown. It then follows the elevation contour along the north slope of a sequence of three increasingly higher peaks. On 6-30-13 at 10 am, the fire area looks like a *pick-head* with a point directed toward E (above the green ellipse), and a fat handle from S-SW to N-NE direction. Figure 2 illustrates how the fire propagates during the second night eastward along a constant elevation contour. The insert shows estimated fire perimeter on 6-30-13 at 10 am. [7,8]

2.2 Fire area doubling upon creation of wide fire front

We use Fig. 3 to illustrate how the fire expands into 90^{o} angle over a relatively flat, slightly-downhill inclined area during its fastest area-expansion.

Figure 3 presents two segments of two US Geological Survey maps, with green (actually yellow on processed map) indicating vegetation. The contours are highlighted for 40 ft (12 m) increments in elevation around 6,000, (black), 5,800 (red), 5,600 (dark blue), 5,400 (green), 5,200 (brown), 5,000 (pink), 4,800 (blue) and 4,600 (orange) feet. Around 10 am, the fire front seems to be delineated by the 5,200-ft contour below the *pick*, and 5,000-ft contour above the *pick*. During daytime, the wind takes force again at 10 mi/hr in N-NE direction. The general area NE and E of the three peaks that form the *pick* head is gently sloping downhill, decreasing in elevation by approximately 400 feet (133 m) over distance of 3 miles (5 km) in N direction, 3 mi (2 km) in NE direction and 2 miles (3 km) in E direction.

Wind in N and NE direction has speed components of 2/3 of the principal wind direction, toward N-NE, i.e., 7 mi/hr. During the ensuing 3 hours, the fire front moves N on the left side of the area, along the equal elevation contours. Along the central N and NE area, it is propelled by the wind along a downhill slope of about 133 ft per mile, or 1/40. This wind also has a downhill direction, because it has acquired vertical component upon climbing uphill the steep Weaver Mountains, with ridge running N-NW to S-SE there. When the wind climbing up the slope at 45^o tops the ridge, it generates turbulence there. Furthermore, it acquires some upward momentum until rolling down along the back slopes of the three peaks that form the *pick*-shape fire area.

On the western perimeter, the fire front circumvents another 6,000-ft peak, following along a 5,800-ft contour.

The smaller side image shows estimated fire perimeter on 6-30-13 at 1 pm. (From [7]) Some contours are visible also on the inset, with cartographic shading decreasing their visibility to some degree.

2.3 Reversal of wind direction (outflow boundary from NE) and accumulated combustion energy

We relay on Fig. 4 to describe how the fire raged upon the change in wind direction, this time moving uphill with a very small angle of inclination, the ideal case for propagation of brush fires.

Figure 4 presents a composite of four segments of four US Geological Survey maps, with green (actually yellow on processed map) indicating vegetation. The contours are highlighted for 40 ft (12 m) increments in elevation around 6,000, (black), 5,840 (red), 5,600 (dark blue), 5,400 (green), 5,200 (brown), 5,000 (pink), 4,800 (blue) and 4,600 (orange) feet. Three factors make the environmental conditions at 4 pm on 6-30-13 ideal for the fire propagation. First, the wind reverses direction by 180^o: previously coming from S-SW to N-NE, now blowing from N-NE to S-SW with double or possibly quadruple speed. The NE area of the map is bounded on three sides by 4,600-ft contours (orange), with only two additional contours that bring the general elevation to about 4,500 ft. The plateau is not burning because it is covered by irrigated agricultural land, allowing wind to pass close to the ground without ignition. Second, the elevation is increasing gradually along the new wind direction. The corridor along freeway is not burning, being free of fuel and with wind arriving from agricultural areas.

There is an overpass at 4,900-ft elevation, among the three peaks above which the burnt area assumed a shape of the *pick*. There, the wind passes with increased speed (according to Bernoulli's equation). Last, and most significant, the fire has just travelled alongside the same area, leaving some fuel still burning and plenty of energy stored in surrounding air. The fire-in-progress is providing massive amount of heat, ready to be provided for the combustion of new fuel. The insert shows estimated fire perimeter on 6-30-13 at 1600. (From [7]).

3. PROPAGATION OF WILD FIRES ON TERRAIN WITH SIGNIFICANT GRADIENTS: PROPOSED MODEL

We deduce five principles of fire propagation, applicable to fire propagation in mountainous terrains and environments with non-uniform elevation and low fuel height.

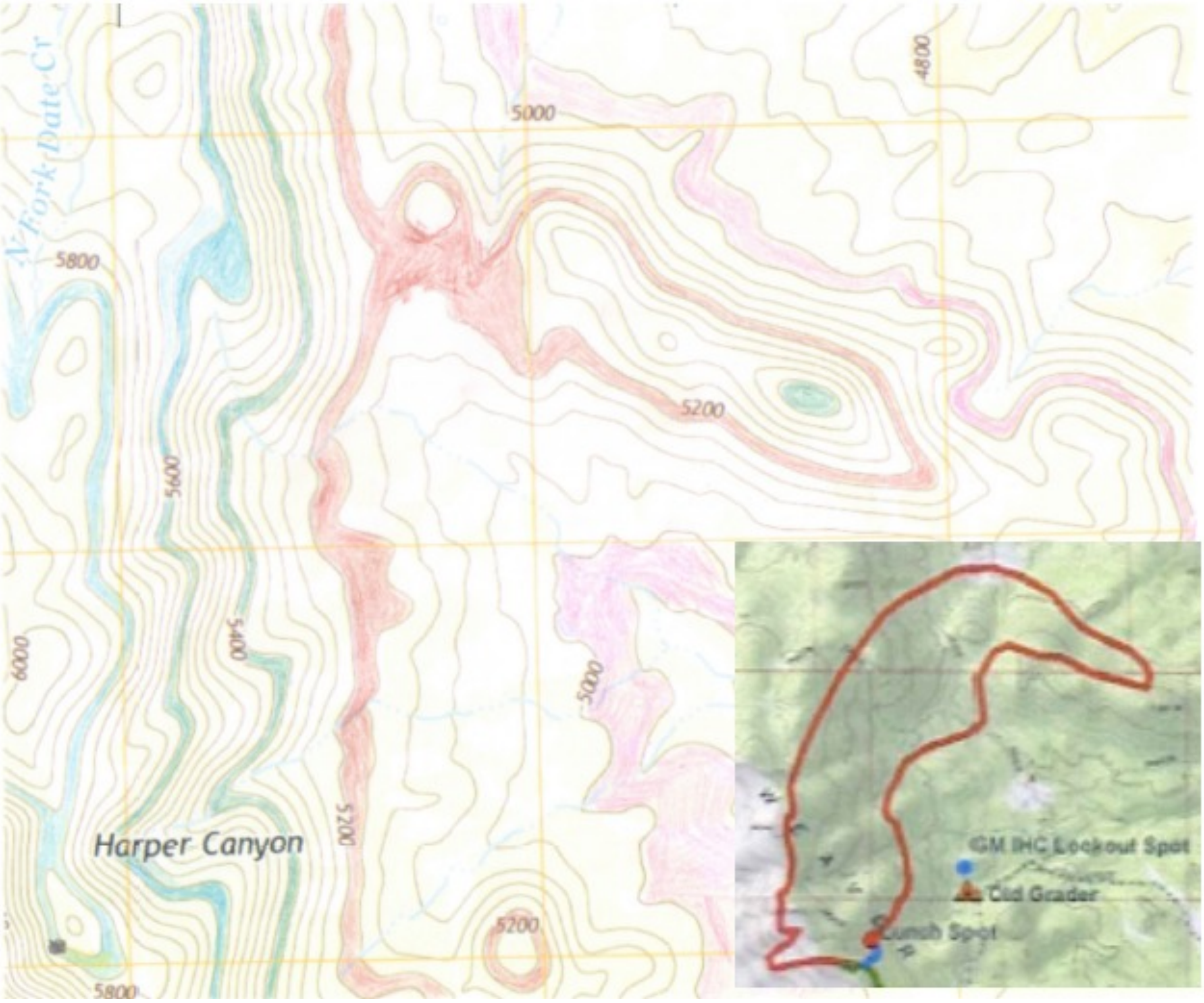

Fig. 2. A segment of the US Geological Survey map, with green (actually yellow on processed map) indicating vegetation (a high chaparral). The lightening strikes on June 28, 2013 at 5:30 pm at about 5,860-ft elevation, indicated with a dark square in the lower left corner. The contours are highlighted for 40 ft (12 m) increments in elevation at 5,800, 5,600, 5,400, 5,200, 5,000, and 4,800 feet. During the first night, the fire spreads slowly around the area of lightening strike. Then it propagates along the equal elevation contours. With terrain sloping gently down-hill on the ridge running S-SE to N-NW, the fire is nudged slowly to lower elevations (with highest gradient), until during the second night it comes to the saddle point at 5,200 ft, in brown. It then follows the elevation contour along the north slope of a sequence of three increasingly higher peaks. On 6-30-13 at 10 am, the fire area looks like a *pick-head* with a point directed toward E (above the green ellipse), and a fat handle from S-SW to N-NE direction. The insert shows estimated fire perimeter on 6-30-13 at 10 am. (From [7,8])

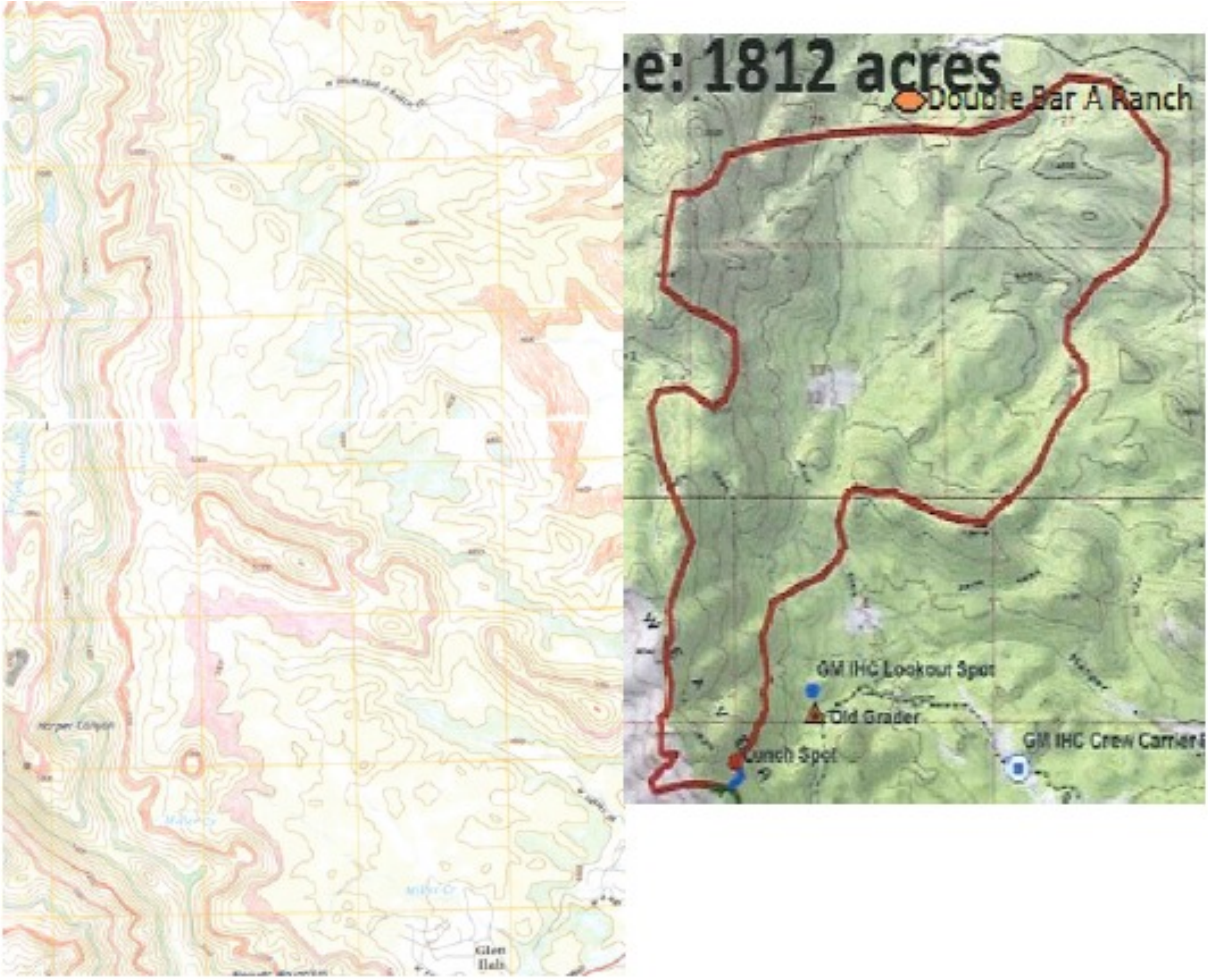

Fig. 3. A segment of two US Geological Survey maps, with green (actually yellow on processed map) indicating vegetation. The contours are highlighted for 40 ft (12 m) increments in elevation around 6,000, (black), 5,800 (red), 5,600 (dark blue), 5,400 (green), 5,200 (brown), 5,000 (pink), 4,800 (blue) and 4,600 (orange) feet. Around 10 am, the fire front seems to be delineated by the 5,200-ft contour below the *pick*, and 5,000-ft contour on top of the *pick*. During daytime, the wind takes force again at 10 mi/hr in N-NE direction. The general area NE and E of the three peaks that form the *pick* head is gently sloping downhill, decreasing in elevation by approximately 400 feet (133 m) over distance of 3 miles (5 km) in N direction, 3 mi in NE direction and 2 miles (3 km) in E direction. Wind in N direction and in NE direction has speed component of 2/3 of the principal wind, i.e., 7 mi/hr. During these 3 hours, the fire front moves N on the left side of the area, along the equal elevation contours. Along the central N and NE area, it is propelled by the wind along a downhill slope of about 133 ft per mile, or 1/40. This wind also has a downhill direction, because it has risen uphill the steep Weaver mountains, with ridge running N-NW to S-SE. When the wind tops the ridge, it produces turbulence there. Furthermore, it keeps some upward momentum until rolling down along the back slopes of the three peaks that form the *pick*-shape fire area. On the western perimeter, the fire circumvents another 6,000-ft peak, along a 5,800-ft contour. The smaller side image shows estimated fire perimeter on 6-30-13 at 1 pm. (From [7]) Some contours are visible there also.

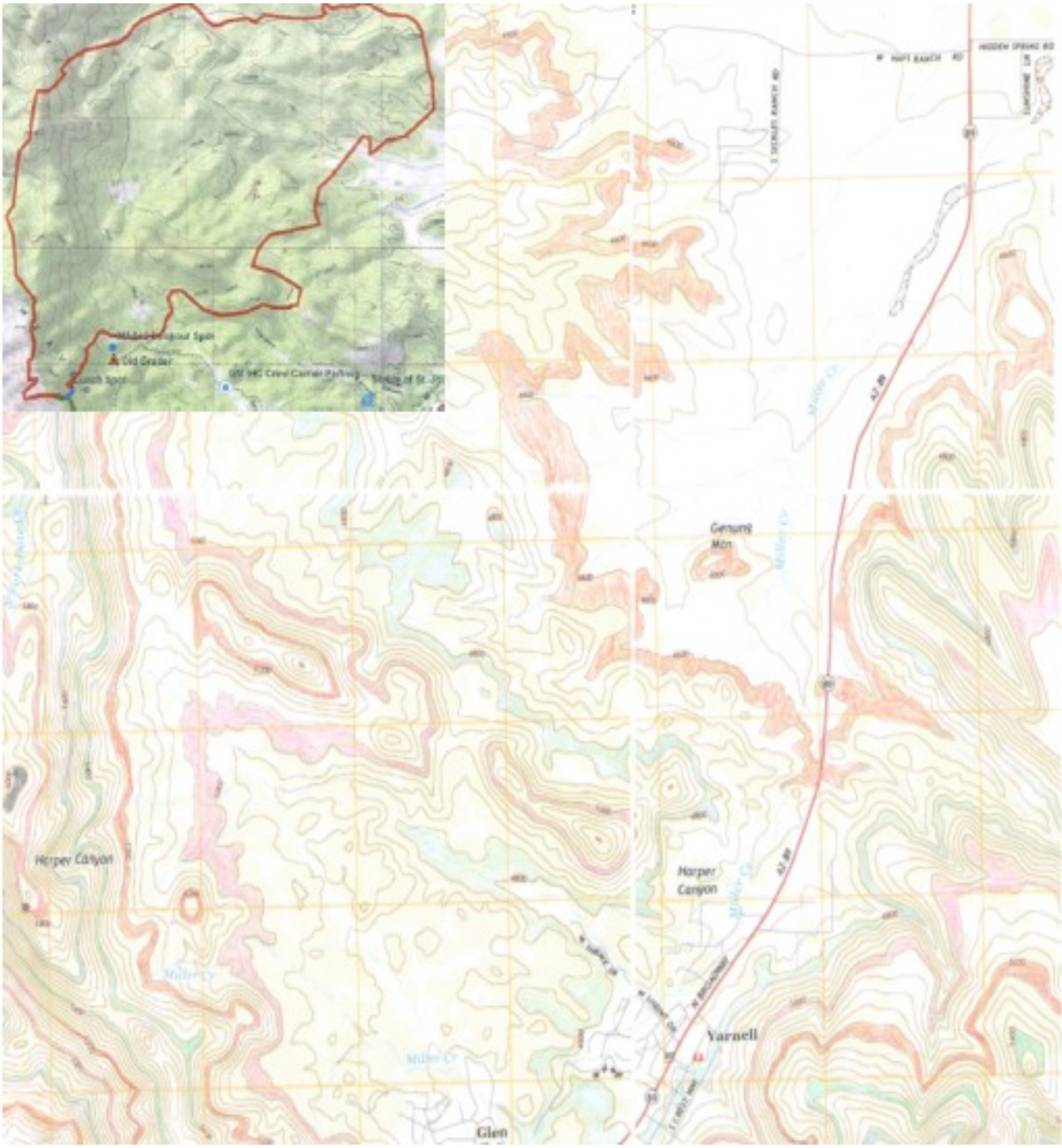

Fig. 4. The NE area of the map is bounded on three sides by 4,600-ft contours (orange). There is an overpass at 4,900 ft elevation, next to the three peaks above which the burnt area assumed a shape of the *pick*. There, the wind traveling in S-SW direction passes over it with increased speed (prediction of Bernoulli's equation).

First, microclimate at the level of fuel height is established over the surface topography with local winds different from the prevailing area winds. This means that the weather advisory provided by the distant meteorological stations may not correspond to the local situation. This discrepancy may have severe consequences for local assessment of the fire conditions and fire management strategies.

Second, the fire in areas sheltered from the outside and prevailing area winds propagates along the equal elevation contours. Such areas might include regions just below the ridge when the wind blows from the other side of the ridge. Also included would be canyons, and springs (in Arizona only occasionally with water).

Third, in regions of high elevation gradients and low-lying fuels, fire propagates reluctantly (seldom) to higher elevations, except by physical transfer, facilitated by local wind. This is in stark contrast with the textbook cases of fire management where the fire is usually shown to propagate up slightly elevated terrain: there the heat, generated during earlier combustion stage, rises and provides heat for fire initiation over the virgin fuel.

Fourth, fire moves slowly to lower elevations, doing so only by physical transfer of air-borne ambers and burning fuel (i.e., burning branch falls down on a lower ground). For the same absolute value of the high gradient, it is more likely that the fire would propagate downhill than uphill, due to assistance of gravity.

Fifth, local micro-winds, generated partially by the combustion processes, propel fire displacement when the terrain is essentially a protected plateau. While the near part of plateau is protected from the strong winds by high ridges, the far-lying parts of the plateau might be subject to strong down-bearing winds when those approach surface again.

We propose the following equation to describe fire front propagation over terrains with significant elevation gradients.

$$\bar{v}_{ff}\left(\vec{r}+\Delta\vec{r},t+\Delta t\right)=g\left(\vec{r},t,\Delta\vec{r},\Delta t\right)\left\{\left[\frac{\vec{v}_{lw}\left(\vec{r},t\right)\bullet\nabla f\left(x,y,z\right)}{\left\|\vec{v}_{lw}\left(\vec{r},t\right)\right\|\left\|\nabla f\left(x,y,z\right)\right\|}\right]\bar{v}_{ff}\left(\vec{r},t\right)+p\left(\vec{r},t,\Delta\vec{r},\Delta t\right)\vec{v}_{lw}\left(\vec{r},t\right)\right\}$$

Here we instructed the following symbols and functions:

v_{ff} is a velocity of the fire-front propagation (subscript ff refers to fire front);

v_{lw} is the velocity of the local wind, generated by the local micro-climate;

g is a function that depends on combustion conditions: previous amount rate of fuel burnt and rate of fuel burning; immediately preceding area of the fire (has fire formed a finger within the fuel, or is fire converging from many directions on the current area), and amount of currently available fuel;

p is the probability that an amber or burning fuel will jump onto a nearby area carrying sufficient energy to initiate combustion there. It depends on microclimate and physical terrain characteristics.

4. CONCLUSION

Significant differences between fire propagation along a plane surface and a mountainous one are the establishment of local microclimate and lack of availability of fuel and combustion generated heat. We proposed a model that describes the preferred fire path evolution in mountainous environment.

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